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Enhancing the combustible properties of bamboo by torrefaction

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ABSTRACT

Bamboo has wide range of moisture content, low bulk energy density and is difficult to transport, handle, store and feed into existing combustion and gasification systems. Because of its important fuel characteristics such as low ash content, alkali index and heating value, bamboo is a promising energy crop for the future. The aim of this study was to evaluate the effects of torrefaction on the main energy properties of *Bambusa vulgaris*. Three different torrefaction temperatures were employed: 220, 250 and 280 °C. The elemental characteristics of lignite and coal were compared to the torrefied bamboo. The characteristics of the biomass fuels tend toward those of low rank coals. Principal component analysis of FTIR data showed a clear separation between the samples by thermal treatment. The loadings plot indicated that the bamboo samples underwent chemical changes related to carbonyl groups, mostly present in hemicelluloses, and to aromatic groups present in lignin.

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1. Introduction

Bamboo is viewed as a promising future energy crop (Scurlock et al., 2000) because of its high growth rate (bamboo typically matures within 5–7 years) plus a number of major fuel characteristics such as low ash content, alkali index or heating value. Cultivated as a dedicated energy crop in the northeastern region of Brazil, bamboo is second only to sugar cane in annual energy potential (30.8 TWh) (Anselmo Filho and Badr, 2004) and its production is more sustainable than that of pine (Guarnetti, 2007). Nevertheless, it is important to use efficient biomass conversion technologies to take advantage of bamboo's characteristics. Among existing technologies to improve biomass for energy production, torrefaction is one of the most efficient means to recover energy from biomass. Torrefaction is a thermal pretreatment process that enables energy densification of biomass and biomass homogenization (Uslu et al., 2008; Yan et al., 2009). It is a mild pyrolysis process carried out at temperatures ranging from 200 to 300 °C under atmospheric pressure in the presence of low or not oxygen. The advantages of torrefaction include removing water uptake properties, eliminating biomass decomposition, reducing grinding energy requirements (Arias et al., 2008; Phanphanich and Mani, 2011; Repellin et al., 2010), and creating a more uniform fuel for gasification (Couhert et al., 2009) or co-firing for electricity (Bergman et al., 2005). Torrefaction is influenced by many parameters including the composition and physical properties of the biomass and operating conditions (Esteves and Pereira, 2009). Bamboo is considered to be a composite material because it consists of cellulose fibers embedded in a lignin matrix. During torrefaction of lignocellulosic materials, the main decomposition reactions affect the hemicelluloses. Lignin and cellulose may also decompose in the range of temperatures at which torrefaction is normally carried out, but to a lesser extent (Rousset et al., 2009). The final product is the remaining solid, which is often referred to as torrefied biomass. It has attractive properties such as improved heating value and low moisture content, and is easy to reduce in size.

Torrefaction of bamboo is mostly seen as a way of making the product more resistant to fungal attacks (Salim et al., 2010; Wahab et al., 2005). Few studies have focused on bamboo torrefaction for the production of energy (Sridhar et al., 2007).

The purpose of this study was thus to increase our knowledge of bamboo torrefaction for energy production. Experiments were carried out in a lab-scale reactor adapted for large samples. We investigated changes in the physical and chemical characteristics of bamboo (*Bambusa vulgaris*) samples when subjected to mild pyrolysis treatment in the temperature range of 220–280 °C. Weight loss was measured during the process using a special device adapted for bamboo. The torrefied bamboo was further characterized in terms of its composition and calorific value. Both proximate and ultimate analyses were used to compare torrefied bamboo characteristics with other solid fuel. Fourier Transform Infrared spectroscopy (FTIR) and conventional chemical analyses of the solid products were conducted to compare the combined effects of temperature and reaction time to the chemical changes.

The results of this study could be used to make recommendations for torrefaction conditions of bamboo.

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2. Methods

2.1. Samples

Three mature bamboo plants (*Bambusa vulgaris*) obtained from a forest farm in north-eastern Brazil were selected as the raw material for the study. This species is the most widely used for reforestation in Brazil. The stems sampled were at least five meters long and ranged from 5 to 15 cm in diameter from the top to the base. Each bamboo stem was divided into three sections representing the top, the middle part and the base of the plant. From each of these sections, three samples of approximately 20 cm in length were extracted. Nine trials were conducted to pyrolyse a total of 81 samples. The small dimension of the bamboo samples in the radial direction allowed to avoid heat transfer limitation, thus ensuring homogeneous treatment throughout the section.

2.2. Torrefaction protocol

In the present study, the torrefaction of the bamboo was achieved using a laboratory scale reactor detailed in a previous paper (Rodrigues and Rousset, 2009). The bamboo sections were heated at different temperatures in an inert environment. In addition, samples without any thermal treatment were used as control. Precise temperature control was ensured by equipment allowing a high heat transfer coefficient at the sample interface as described in (Rousset, 2004). The equipment used in this study enabled us to measure simultaneously the dynamics of biomass weight loss and the temperature inside the biomass throughout the course of the experiment. When torrefaction was performed, a temperature program, consisting of an isothermal heating period, was applied: the temperature was raised from 20 °C to the appropriate torrefaction temperature (i.e. 220, 250 and 280 °C) with a constant heating rate (3 °C min^{-1}). Once the oven chamber reached the torrefaction temperature, the bamboo samples were torrefied for 1 h followed by a natural cooling period to ambient temperature. From a practical point of view, the investigated biomass torrefied in less than 1 h with light torrefaction (240 °C), which is appropriate for producing high energy density fuels (Chen and Kuo, 2010). From the recorded distribution of weight and temperature, thermogravimetric analyses versus biomass temperature were obtained. After torrefaction, the material was ground and sieved to a maximum particle size of 60 mesh. The torrefied material was stored in a desiccator at room temperature until chemical analysis.

2.3. Chemical analysis

All the analytical characterizations were carried out on extractive-free milled samples. Gross Calorific Value (GCV) was determined on the basis of thermal energy generated by complete combustion of the sample in a constant pressure chamber. A PARR 1261 bomb calorimeter was used in agreement with the NBR 8633/84 standard. Proximate/ultimate analyses were performed and the heating value (dry basis) was measured. Proximate analysis was conducted to determine the fraction of ash (Ash) and volatile matter (VM). The fixed carbon (FC) content was obtained by difference. The values of proximate analysis were obtained in accordance with the procedure of the Brazilian Association of Technical Standards ABNT NBR 8112/86. The ultimate analysis provides the composition of the biomass in wt.% of carbon, hydrogen and oxygen (the major components) as well as sulphur and nitrogen. Ultimate analysis values were obtained in accordance with the European procedure XP CEN/TS 15104. The lignin content of the samples was measured according to the standard methods developed by NREL LAP-003 and NREL LAP-004 described respectively by Templeton and Ehrman (1995) for acid-insoluble lignin and by Ehrman (1996) for acid-soluble lignin. The infrared measurement procedure is described in Labbé et al. (2006). Multivariate techniques such Principal Component Analysis (PCA) was employed to extract useful information from the spectral data set. PCA is essentially a descriptive method. The main goals of this procedure are to find relationships between the different parameters (objects and variables) and to detect possible clusters or trends within objects and/or variables.

3. Results and discussion

3.1. Raw material characteristics

Proximate/ultimate analysis, heating values and lignin content of the untreated biomass are listed in Table 1. The moisture content of the samples ranged from 15% to 29% depending on the location of the sample in the bamboo stem. Ash contents ranged from 1.4% to 2.4%, with significant difference regarding the height at which the sample was located in the stem. Other studies showed similar results with the highest value in the samples located at the top of the stem (Xiaobo, 2004). Compared to other biomass feedstocks, ash contents were slightly higher than those found in woody biomass materials. Many herbaceous biomass materials (grasses and straws) have higher ash contents (Scurlock et al., 2000). The volatile matter (VM) contents of all of the bamboo samples were around 80% and a correlation was found between volatile matter content and the location of the bamboo sample in the stem.

All the bamboo samples had very similar gross calorific values. These heating values are comparable to, but slightly lower than, most woody biomass feedstock and higher than most grasses and straws (Nordin, 1994). The ultimate analyses of the bamboo samples did not show correlation between values obtained and the location of the sample in the stem. The N content was globally very low at all heights but slightly higher (0.27%) at the top section. Height would have a significant effect on holocellulose and cellulose content (Li, 2004).

3.2. Torrefaction of biomass

The averaged gravimetric yields denoted (η_m) for each bamboo plant (mixture of each location) are listed in Table 2. These results are compared to published data on a standard biomass (eucalyptus). Gravimetric yield (η_m) is the ratio of torrefied wood mass (M_{tor}) to initial feedstock mass (M_{cont}), dry at 0%. It is expressed in % by the equation $\eta_m = (M_{tor}/M_{cont.}) \times 100$. Fig. 1 illustrates the temperature inside the reactor and the mass loss of the solid during torrefaction. The similarity between the temperature profiles of the bamboo and the operating temperature demonstrated the efficiency of the torrefaction system with excellent control of the parameters. At 220 °C, there was only a slight reduction in mass of around 9% while the reduction was 4% for eucalyptus. However, increasing temperature had a significant effect on the thermal decomposition of the bamboo. At temperatures of 250 and 280 °C, the averaged mass losses were respectively 23% and 39% while they were only 12% and 20% for eucalyptus. Although the greatest rate of mass loss occurred during the temperature ramping stage, the isothermal period accounts for the greatest overall mass loss. These results are in agreement with those of previous studies (Bridgeman et al., 2008; Chen and Kuo, 2010). Rodrigues and Rousset (2009) found that the impact of torrefaction on bamboo is more pronounced than on woody biomass. Bamboo is more reactive than other biomass such as coconut shell or wood. A recent study showed that overall mass loss could be a relevant

Table 1
Average values of proximate/ultimate and chemical analysis and heating value of untreated bamboo. For each group, the means with the same letter were not significantly different at 5% ($\alpha = 0.05$). *Values from (Li, 2004).

		Bamboo (*Bambusa vulgaris*)			
		Location			
		Bottom	Middle	Top	Mixture
Proximate analysis (wt.%, db)	Moisture	29.59a	15.68c	15.31c	20.19b
	VM	79.86b	81.14a	79.08b	80.13a,b
	FC	18.19a,b	17.43b	18.52a	17.75a,b
	Ash	1.95b	1.43c	2.40a	2.12b
Ultimate analysis (wt.%, db)	C	46.92a	47.04a	46.47a	46.78a
	H	6.36a	6.42a	6.34a	6.38a
	N	0.18b	0.18b	0.27a	0.25a
	O	46.54a	46.36a	46.92a	46.59a
Chemical analysis (wt.%, db)	Lignin	27.22a	26.88a	26.93a	26.65a
	Cellulose*	46.08a	47.65b	47.91c	
	Hemicelluloses*	69.94a	72.50b	73,65c	
GCV (Mj/kg, db)		18.32a	18.47a	18.37a	18.21a

Table 2
η_m is averaged gravimetric yield (%) of the three bamboo plants at different torrefaction temperatures. The height of the sample in the bamboo stem was not taken into consideration. *Results from Rodrigues and Rousset (2009).

	Treatment	Duration (min)	220 °C	250 °C	280 °C
η_m (wt.%)	Bamboo 1	60	93	78	67
	Bamboo 2	60	88	76	60
	Bamboo 3	60	91	76	57
	Eucalyptus*	60	96	88	80

parameter to determine the effect of torrefaction conditions (temperature and duration) (Almeida et al., 2010).

3.3. Energy characteristics of torrefied bamboo

The mass and energy yield are the most important parameters in evaluating torrefaction of bamboo. The organic part of the biomass contains all the (reactive) chemical energy and, during torrefaction, part of this energy is removed in the form of reaction products (gas and solid). The results of the gross calorific value (GCV) and the energy yield calculation (η_e) of the untreated and treated bamboo by temperature of torrefaction for each height location are presented in Table 3. At 220 °C, 250 °C and 280 °C, the averaged values were respectively 19.5, 21.3 and 23.2 MJ/kg. These findings are in agreement with those of other studies (Brito et al., 1987). There is an increase in GCV with an increase in temperature. No correlation was found with the height location.

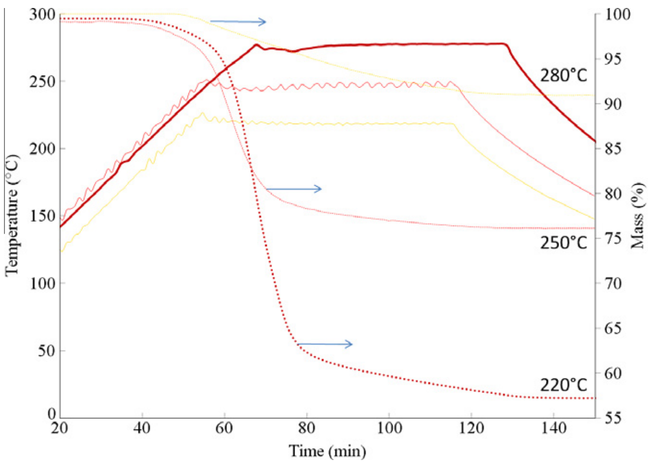

Fig. 1. Averaged temperature (°C) inside the bamboo and mass loss (%) during a 60 min torrefaction treatment at 220, 250 and 280 °C.

A similar trend was observed in the increase in GCV at each location. Energy yield (η_e) relates mass yield to the highest heating value of wood and is calculated by the formula of Bergman et al. (2005): $\eta_e = \eta_m\,(\mathrm{GCV_{tor}}/\mathrm{GCV_{cont}})$ where η_m is the gravimetric yield, $\mathrm{GCV_{tor}}$ and $\mathrm{GCV_{cont}}$ are respectively the gross calorific value of torrefied and untreated bamboo. As expected, the energy yield was higher at low temperatures with an average of 96%. The changes in energy yield were a function of both the gravimetric yield and the significant increase in heating value. For all products of torrefaction, the energy yield was greater than the mass yield – an effect that became increasingly pronounced with higher temperature treatments. Energy yield behaved as expected with respect to gravimetric yields, with almost 78% of the energy content being retained in the bamboo torrefied at the highest temperature (280 °C). Bridgeman et al. (2008) observed an energy yield ranging from 69% to 77% for reed canary grass at 270 and 290 °C, respectively. In general, all the bamboo results are lower than those obtained with woody biomass where an averaged energy yield of 90% is common (Prins et al., 2006a; Rodrigues and Rousset, 2009).

Fig. 2 shows the % increase in GCV according to the temperature of torrefaction and the location of the sample in the stem. Independent of location, the increase in density of the torrefied bamboo ranged from 5% to 31% respectively at 220 and 280 °C. The highest values were observed for samples obtained from the bottom of the stem. At 280 °C, these values were 31.2%, 23.6% and 25.8% for the bottom, middle and top location, respectively. A 20% increase was observed at 250–260 °C by other authors (Sridhar et al.,

Table 3
Gross calorific value (GCV) average in MJ/kg and energy yield (η_e) in %.

	Control	220 °C		250 °C		280 °C	
		GCV (MJ/kg)	η_e (%)	GCV (MJ/kg)	η_e (%)	GCV (MJ/kg)	η_e (%)
Bottom	18.3	19.8	98.1	21.5	89.8	24.0	80.5
Middle	18.5	19.4	95.2	21.4	88.8	22.8	75.8
Top	18.4	19.4	96.0	21.2	88.5	23.1	77.1
Mixture	18.2	19.3	96.1	21.0	88.4	23.1	78.0

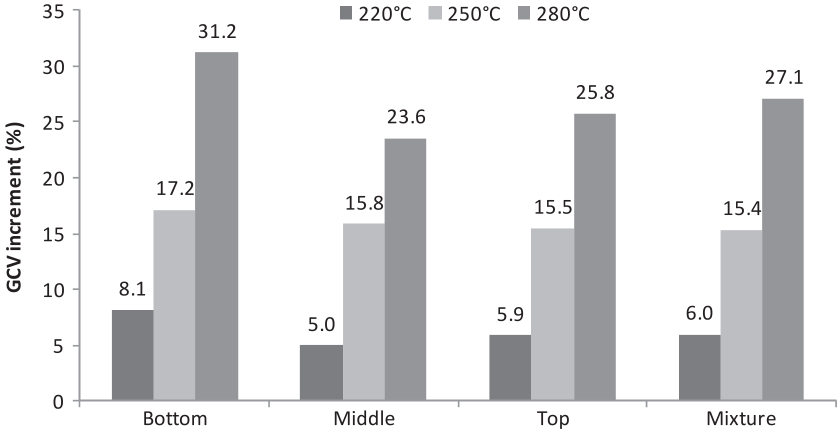

Fig. 2. Increase (%) in GCV of bamboo torrefied at different temperatures according the location of the sample in the stem. The reference measurements are the GCV of raw bamboo listed in Table 2.

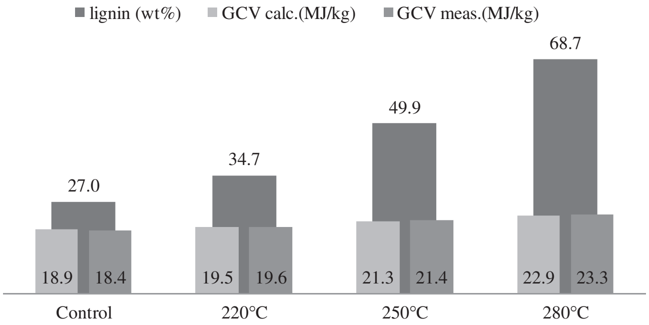

Fig. 3. Linear correlation between the GCV (MJ/kg) of the bamboo and the relative extractive-free lignin content (wt.%) at different torrefaction temperatures. Calc. = calculated and meas. = measured.

2007). For woody biomass, a recent study showed an increase of about 15% in the specific energy content of biomass torrefied at 280 °C (Rodrigues and Rousset, 2009).

Some authors reported a highly significant linear correlation between the GCV of the biomass fuel and the lignin content (Demirbas, 2001; White, 1987). Some equations can be used to determine the higher heating value of extractive-free wood when the Klason lignin content is known. We calculated the GCV (kJ g^{-1}) of the bamboo as a function of extractive-free lignin content (L, wt.%) using the following equations proposed by Demirbas (2001) for light torrefaction (i.e. <240 °C): GCV = 0.0889 (L) + 16.8218 and for severe torrefaction (i.e. 280 °C): GCV = 0.0877 × (L) + 16.4951 where L is the extractive-free lignin content.

Fig. 3 shows a clear correlation between measured lignin content, and measured and calculated GCV using the above equations. The level of Klason lignin in the extract-free samples increased with the severity of the thermal treatment, reaching very high values in the samples treated at 280 °C (close to 70%). Some recent studies showed values of up to 90% in samples treated at 280 °C for 8 h. All the treatments have a significant effect on the relative Klason lignin content with a substantial increase from 28% to 155% in comparison with the untreated material. Such an increase may be due to the selective loss of hemicelluloses components (Rousset et al., 2009). This result suggests that the cell wall polysaccharides were selectively eliminated. The FTIR analysis of the biomass behaviour during treatment confirmed this finding (Fig. 6).

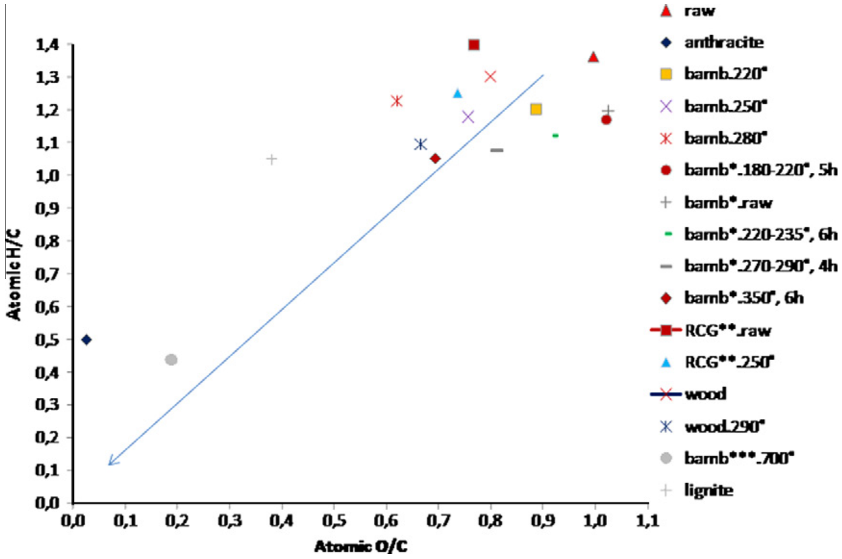

Fig. 4. Van Krevelen diagram for coal, raw biomass and torrefied biomass. *Bamboo analyses are from Sridhar et al. (2007), **RCG (Reed Canary Grass) analyses are from Bridgeman et al. (2008) and ***bamboo analyses are from Xiao et al. (2007). The arrow indicates the increase in energy density.

Table 4
Ultimate analysis at different torrefaction temperatures. The values (%) are the average obtained for each sample location. The percentage change is the relative increment between each treatment. C = carbon; H = hydrogen; O = oxygen; N = nitrogen.

	Control	Torrefaction temperature		
		220 °C %	250 °C %	280 °C %
C	46.80	49.60	53.47	58.43
H	6.38	5.96	5.59	5.10
O	46.60	44.18	40.63	36.13
N	0.22	0.26	0.31	0.34

As expected, the heating values were correlated with the ultimate (Table 4) and proximate analysis (Table 5). Indeed, the results of proximate analysis showed that increasing the temperature reduced the volatile fraction and increased the fixed carbon. Raw bamboo has about 17% of fixed carbon and 80% of volatile matters. After subjecting the samples to the severest temperature (280 °C), the fixed carbon increased to about 38% and volatile matter decreased to 58%. The higher fixed carbon content meant that torrefied biomass produced greater combustion heat during char burnout. These results are in agreement with those published in another study in which the process was carried out at 350 °C resulting in a fixed carbon content of up to 64% (Sridhar et al., 2007).

The progress of torrefaction was also monitored by ultimate analysis (C, H, N, and O). There was an increase in carbon content and a decrease in oxygen and hydrogen elements with the increase in temperature. The nitrogen content remained almost constant. No effect of the location of the samples was observed. Despite larger mass losses, the increase in the carbon content of bamboo at 280 °C was around 23% compared with the raw material. Hydrogen and oxygen losses and the increase in carbon were greater than those observed in another recent study on bamboo torrefaction

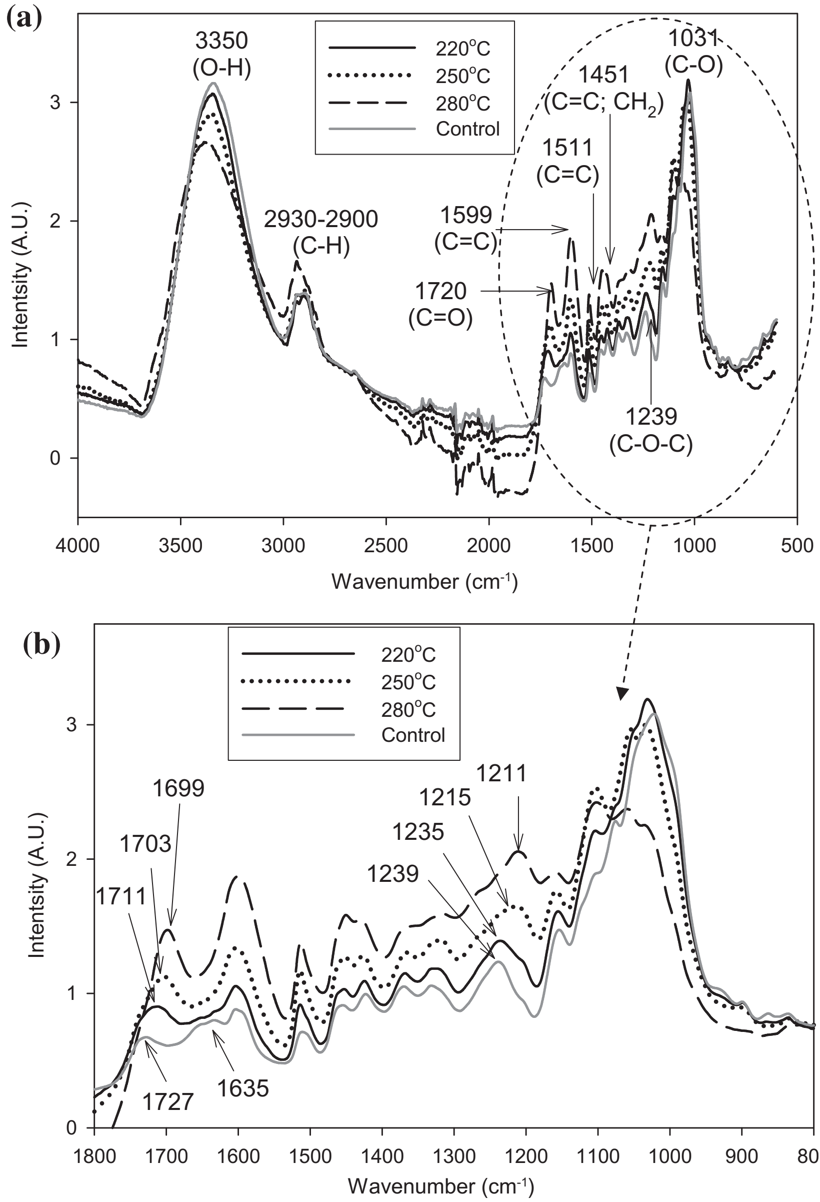

Fig. 5. (a) Fourier transform infrared averaged spectra collected with an Attenuated Total Reflectance (ATR) attachment on bamboo powder between 4000 and 600 cm^{-1}. (b) Zoom on spectra between 1800 and 600 cm^{-1}.

Table 5
Proximate analysis (moisture free basis) of the torrefied bamboo at different torrefaction temperatures and heights. Mixt. is a mixture of the samples from the top, middle and bottom location. For each group, the means with the same letter were not significantly different at 5% ($\alpha = 0.05$). VM: volatiles matters; FC: fixed carbon.

	Control			220 °C			250 °C			280 °C		
Position	VM%	FC%	Ash%	VM%	FC%	Ash%	VM%	FC%	Ash%	VM%	FC%	Ash%
Bottom	79,86ab	18,19g	1,95de	74,78c	23,33e	1,89e	68.09d	29,75d	2,16cde	57,71f	39,29a	3a
Middle	81,14a	17,43g	1,43f	75,82c	21,72f	2,46c	68,63d	29,06d	2,31cd	58,91f	37,65b	3,44a
Top	79,08b	18,52g	2,4c	75,05c	21,67f	3,28ab	67,9d	28,86d	3,24ab	60,68e	35,84c	3,48a
Mixt.	80,13ab	17,75g	2,12cde	75,2c	22,48ef	2,32cd	67,93d	29,19d	2,88a	58,8f	37,78b	3,42a

(Sridhar et al., 2007). One possible explanation is the elimination of the hydroxyl radical group from the polysaccharides, especially hemicelluloses. Hydroxyl radicals are highly reactive and consequently short-lived with the increase in temperature (Nguila Inari et al., 2007). Our results confirmed those in a previous investigation to evaluate the effect of heat treatment on the quantity of free hydroxyl groups present in the wood. The results indicated a significant decrease in the reactivity of heat-treated samples compared to untreated ones. Although this decrease depended on the intensity of treatment, no obvious correlation was observed by the authors between weight gain due to acetylation and mass loss due to treatment (Inari et al., 2009).

Measurements of GCV illustrate the impacts that these changes have on the energy content (Table 3). A plot of the molecular ratios of carbon, hydrogen and oxygen on the Van Krevelen diagram showed that torrefaction leads to a reduction in O/C and H/C ratios; the change in elementary composition of torrefied biomass moved it towards lignite on the Van Krevelen plot (Bridgeman et al., 2008). This is mainly due to chemical changes that occur with heat treatment (Prins et al., 2006b). During the reactions, the liberated compounds contain higher proportions of oxygen and hydrogen than carbon, thus reducing the relative concentration of these elements in the solid residue. In our study, the characteristics of the torrefied bamboo began to resemble those of low rank coals in terms of the Van Krevelen coal rank parameter (Fig. 4). In agreement with others studies (Demirbas and Demirbas, 2004), one can conclude that there is a highly significant correlation between the GHV of the lignocellulosic fuels and their carbon or (carbon + hydrogen) contents.

3.4. FTIR analysis of torrefied bamboo

Fourier transform infrared spectroscopy (FTIR) was used to investigate the changes in the chemical structure of the samples during thermal treatment. Fig. 5a shows infrared spectra collected during heat treatments of bamboo. Differences in the spectra with thermal treatment were mainly observed in the fingerprint region of the spectra. While the intensity of the OH bands around 3350 cm^{-1} decreased with the thermal treatment, the intensity of several bands increased (1720, 1599, 1511, 1239, 1451 cm^{-1}) demonstrating that chemical changes appear during the treatment. These changes can be attributed to the chemical decomposition of polysaccharides. Hemicellulose is the most reactive of the three lignocellulosic components found in biomass, and during torrefaction it undergoes the most significant decomposition reactions. In addition, two major bands shifted to lower wavenumbers with the treatment (the C=O band from 1727 to 1699 and the C–O–C band from 1239 to 1211, respectively) confirming chemical changes around this functional groups during the thermal treatment. Thus the composition of biomass fuels has a significant impact on the amount of both solid residue and the changes in volatile and gaseous products during torrefaction (Di Blasi, 2008). Because of the number of samples and heat treatments, multivariate analysis was used to compare the spectra and to extract chemical information.

Principal component analysis (PCA) was carried out on the set of the FTIR spectra. PC1 described a considerable amount (91%) of the total variance and revealed a particularly interesting trend, as can be observed in the scores plot in Fig. 6a. Four distinct clusters were obtained along PC1. On the left (negative along PC1) are the samples with high thermal treatments (250 and 280 °C), and on the right (positive along PC1) the low temperatures (220 °C and untreated raw samples). PC1 was the most informative latent variable for the description of the thermal treatment of the samples, independent of sample height. The highest dispersion was obtained at 280 °C, in other words, this treatment changed the chemistry of the bamboo the most. Similar results were obtained with woody biomass (Rousset et al., 2011). The loadings plot (Fig. 6b) shows the chemical features that are responsible for grouping the samples along PC1. The intensity of the loadings

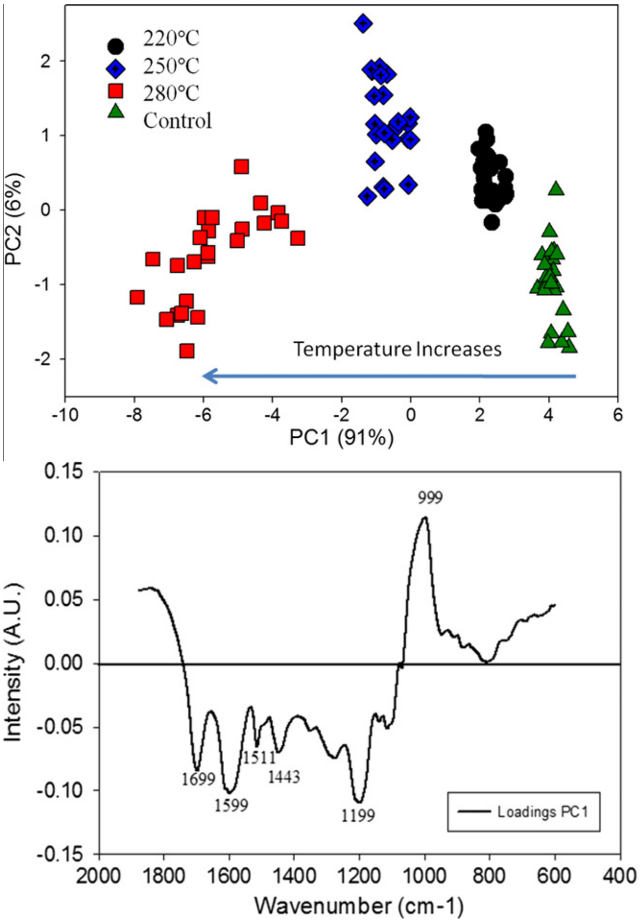

Fig. 6. (a) Scores plot of the first two PCs obtained by PCA of the mid-infrared spectra measured on the heat-treated samples and control. (b) Loadings plot of the first principal component (PC1).

showed how well a variable (wavenumber) is taken into account by the model components. They can be used to understand how much each wavenumber contributes to the meaningful variation in the data, and to interpret variable relationships. From this plot, it is possible to obtain information about the chemical aspects involved in the thermal process (Labbé et al., 2006). The 1127–927 cm^{-1} loadings region is the most important region in distinguishing the different thermal treatments as shown in Fig. 5b.

The absorption bands in this spectral interval are typically assigned to the C–O stretching vibration in cellulose and hemicelluloses. Additional vibrations appear in several regions of the loadings at 1191, 1287, 1583, and 1695 cm^{-1}. If a variable has a positive loading, it means that all samples with positive scores have higher value than averaged values for that variable and all samples with negative scores have lower value than averaged values for that variable. On the basis of this rule and the positive band at 999 cm^{-1}, one can conclude that the samples in the right cluster (untreated and 220 °C) have higher cellulose and hemicelluloses content than the samples in the left cluster (250 and 280 °C). Based on the negative bands associated with lignin at 1599 and 1511 cm^{-1}, samples treated with higher temperatures possess higher lignin content. These observations are consistent with those reported in the literature (Labbé et al., 2006). Between 250 and 280 °C, hemicelluloses and cellulose are degraded, while at higher temperatures (>300 °C), lignin is degraded (Rousset et al., 2009). FTIR could be used as a relevant parameter to synthesize the combined effects of temperature and duration of treatment.

4. Conclusions

Light and severe torrefaction of bamboo were studied to identify the weight loss dynamics of the biomass and the impact of torrefaction processes on energetic properties. Bamboo biomass undergoes greater alterations in its properties during torrefaction than woody biomass in terms of mass loss and chemical composition. In addition, bamboo underwent greater changes in terms of elemental composition and increases in energy content than woody biomass. A clear correlation between lignin content and measured GCV was demonstrated. The FTIR technique combined with PCA is a powerful and rapid tool for monitoring chemical changes in wood during thermal treatment.

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